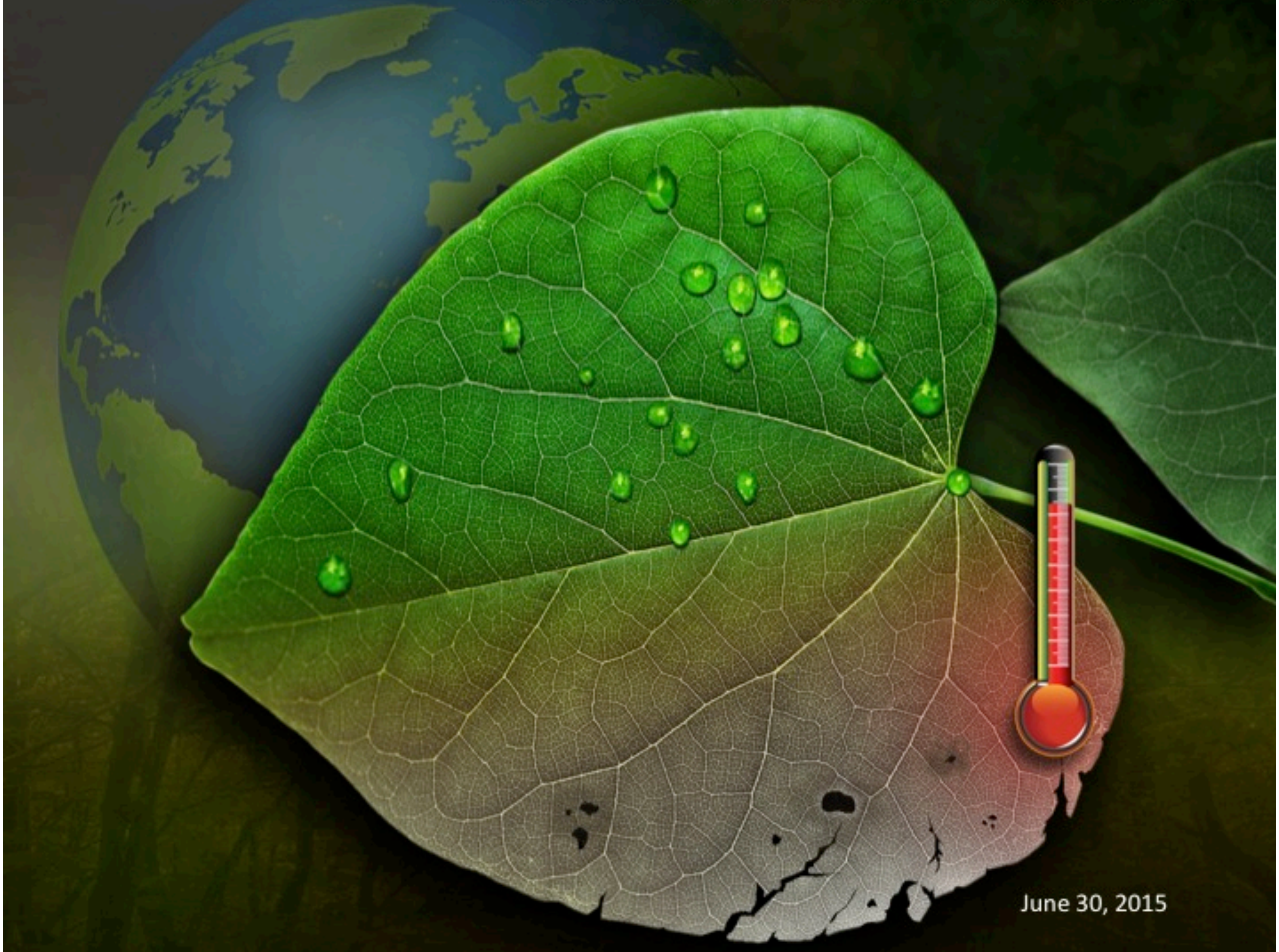
JPL D-94803

ECOSTRESS

ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station

Level-1 Focal Plane Array and Radiometric Calibration Algorithm Theoretical Basis Document (ATBD)



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Change History Log

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Draft	07/07/2015	TLogan	Miscellaneous edits
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Abstract

The ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) concept was selected as a NASA Earth-Ventures Instrument (EV-I) Class-D mission for operation on the International Space Station (ISS). The mission's goal is to investigate vegetative water stress through the measurement of plant temperatures. The ECOSTRESS instrument was designed and built at the Jet Propulsion Laboratory (JPL) and consists of a thermal infrared (TIR) multispectral scanner with five spectral bands operating between 8 and 12.5 µm and one Shortwave Reflectance band (SWIR). The imagery will be acquired at a spatial resolution of 38m x 68m with a swath width of 402 km when calculated from the nominal altitude of the International Space Station (400 +/- 25 km). Subsequent output products will have an approximate ground resolution of 70m (~75x68m) with an along-track coverage of 400 km.

This algorithm theoretical basis document (ATBD) describes the Level 1 radiometric calibration of the ECOSTRESS TIR imagery. The calibration process involves removing (correcting) non-uniform light measurement between individual pixel detectors on the focal plane array (FPA) and adjusting those values to represent radiometrically correct radiance measurements by using a two-point linear extrapolation derived from two on-board Blackbodies. Based on Laboratory experiments, the radiometric calibration is expected to support an accuracy of one degree Kelvin (at 300° K).

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1 Introduction

The ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) is a NASA mission that deploys an advanced imaging spectrometer on the International Space Station to monitor environment stress on the Earth using Thermal Infrared (TIR) wavelengths. The planned science products include Earth surface radiance, temperature, emissivity, evapotranspiration, water use efficiency, and an evaporative stress index. To measure radiance, the instrument uses a continuously rotating scan mirror in a push-whisk configuration to direct light from the telescope through six narrowband interference filters to the Focal Plane Array (FPA). The focal plane consists of 8x16x256 arrays of Mercury Cadmium Telluride (MCT) detectors of CMOS (complementary metal oxide semiconductor) manufacture. The ECOSTRESS FPA was originally developed at JPL as the "Prototype HyspIRI-TIR (PHyTIR)" instrument and has been tested in the Laboratory and documented by Johnson, et al [1]. A summary of the ECOSTRESS spectral imaging statistics are provided as Table 1.

Band Number	Center Wavelength (microns)	Bandwidth (microns)	
			Pixel GSD (Nadir):
			Collection: 37.65 x 68.51m
1	1.660	0.37	Product: 75.3 x 68.51m
2	8.285	0.34	**Earth Coverage:**
3	8.785	0.35	400 x 402km
4	9.060	0.36	**Dynamic Range:**
5	10.522	0.54	14bit Integer
6	12.001	0.52	

Table 1: The ECOSTRESS Mission Spectral Imaging Statistics.

Level-1 (L1) FPA (Focal Plane Array) Calibration is the process of removing (correcting) non-uniform light measurement between individual pixel detectors on the focal plane array. L1 Radiometric Calibration is the process of relating the uniform values received from the focal plane detectors to a standard measurement. For visual (VIS), near-infrared (NIR) and shortwave infrared wavelengths (SWIR) the conventional FPA calibration approach is to apply Dark Current and Flat-Field procedures, then perform a separate vicarious radiometric calibration to measure scene radiance. However, Thermal Infrared (TIR) imaging systems (such as the ECOSTRESS instrument) typically have on-board Blackbody temperature sources which are used to radiometrically calibrate the image and perform basic FPA calibration in one step. Subsequent FPA corrections are only necessary if there are non-responsive pixels, post-imaging artifacts, or if the Blackbodies should unexpectedly degrade. Note that preparations of Level-2 products (i.e., Land Surface Temperature and Emissivity) require the application of additional calibration algorithms as described by Hulley and Hook [2] and are outside the scope of this document.

2 Pixel Travel Path and FPA Reserves

Unlike the conventional Frame Camera in which the focal plane closely defines the size of the output image, the ECOSTRESS rotating scan mirror illuminates a relatively small focal plane and combines multiple FPAs to produce a composite image. A single-band L1A "image" delivered to the ground is 5400 pixels (lines; Y; across-track) by 11264 pixels (samples; X; along-track) and is a mosaic of 237,600 focal planes (where each FPA is 1x256 pixels). The travel path of a pixel from photon to L1A radiance product is shown in Figure 1. The total Level-0 data delivered to the ground (approximately every minute) is five TIR bands and one Reflectance (SWIR) band, plus associated Blackbody calibration and related metadata.

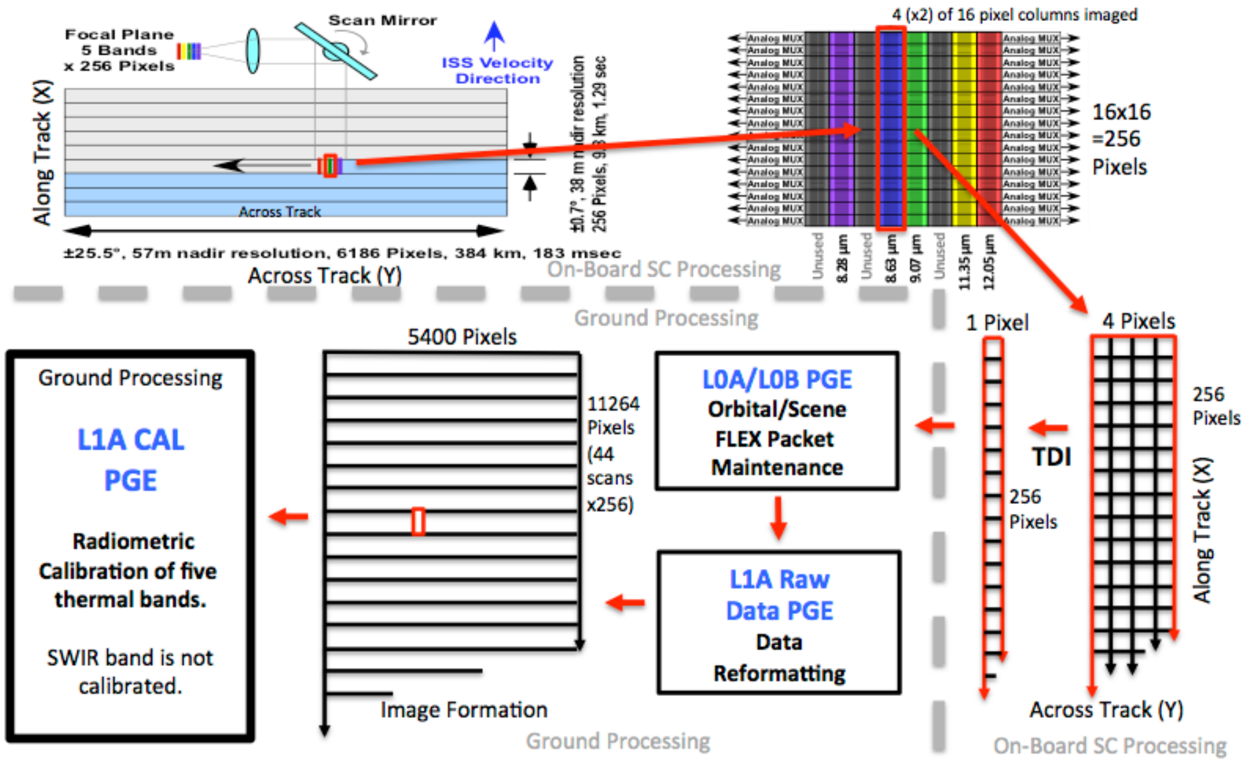

Figure 1: Travel path of an ECOSTRESS pixel from photon to L1A CAL Radiometric Calibration PGE (Product Generation Executive). Only one band is shown for clarity (actual data flow includes six bands plus Blackbody calibration metadata).

The FPA diagram in (the upper right corner of) Figure 1 shows the eight available focal plane band/columns. Six bands are currently identified for use leaving two in reserve. Each of the eight FPA band/columns is 16 by 256 pixels, with 4 of the 16 pixels illuminated to produce image product. A fast clock rate and associated settling times require that the immediately following 4-pixel column be skipped such that each one of the 4 illuminated pixel columns actually consumes a set of two columns. This means that (4x2=) 8 of the 16 pixel columns in each FPA band are used for imaging and the remaining 8 pixel columns are available as backup. This 50% reserve combined with the two unused band/columns provides an exceptional FPA contingency.

For each focal plane band/column a 4x256 14-bit integer "image" is read and summed across-track (Time Delayed Integration; TDI) to a 1x256 pixel image (Figure1; Bottom Right). The data stream is downloaded to the Ground Data System (GDS) where the data are organized into Orbit and Scene files (L0A/L0B PGE) reformatted (L1A RAW PGE), and corrected for missing or invalid data. Each image becomes a concatenation of 5400 (1x256 pixel) across-track focal planes (one "scan"), with 44 successive scans completing a full L1A image. The resultant image is 5400 samples by 11264 lines (by 6 bands) and is essentially a mosaic of 237,600 embedded focal plane images (per band). Radiometric calibration (L1A CAL PGE) begins once the "L1A Raw" process is complete and all the image data are properly formatted.

3 Algorithm Descriptions

The three algorithmic processes typically involved with Level-1 calibration include Dark Current (DC) removal, Flat-Field (FF) uniformity correction, and radiometric calibration. For the five TIR bands, the radiometric calibration algorithm uses two on-board Blackbodies of different temperatures to interpolate radiance that inherently corrects for the DC and FF errors. For the SWIR reflectance band, Dark Current and Flat-Field calibrations are normally applied, but as the ECOSTRESS SWIR band is intended for geolocation purposes, only the DC correction is applied, as a full calibration is not required.

3.1 Dark Current Correction

Dark Current (DC) is the sum total of all ambient energy sensed by the focal plane in the absence of incident light and is typically produced by electrical fields generated from the sensor's operating electronics. DC noise tends to increase with increasing temperature and becomes significant above 72 degrees Kelvin. The FPA is therefore maintained at a constant 65K inside a Cryocooler that is further protected by a second enclosing 120K Cryocooler. The Error Budget estimate prepared by Goullioud [3] for Dark Current is 303 electrons/read, which when combined with other noise errors (Read; Photon; Quantization; Optics thermal) amounts to less than 0.1K (at 300 Kelvin post TDI). As noted above, this small DC error is corrected by the per-pixel Blackbody Radiometric Calibration process (see Section 3.3).

For the SWIR case, Dark Current can be measured using the "RetroView" imaging mode, by "Cold Masking" the band filters, or simply treating the SWIR-imaged blackbodies as Dark Current and subtracting them from the SWIR DN (pixel values).

FP1 = FP0 – DC *Dark Current Formula*

Where:

FP0 = Raw Focal Plane image with Dark Current.

FP1 = Focal Plane image with Dark Current removed.

DC = Focal Plane image of Dark Current.

3.2 Flat-Field Uniformity Correction

The purpose of Flat-Fielding (FF) is to correct focal plane pixel artifacts and irregularities relative to a uniform "flat" field of pixels. For the five thermal (TIR) bands, this process is inherent in the radiometric calibration step (in which Blackbodies are used as the uniform flat field), and is therefore replaced by that step. A conventional Flat-Field calibration would only be necessary for the Shortwave Reflectance (SWIR) band.

As noted in Section 3.0 a Flat-Field correction is not required for the ECOSTRESS SWIR band, but should it become necessary, the first step would be to create a Flat-Field calibration file. This is accomplished by dividing the focal plane's pixel measurement of a uniform brightness field by that field's pixel value (where the "uniform field" is the image collected in the field or laboratory of a scene at a fixed integration time or fixed image mean brightness value). The FF correction is performed on a per-pixel basis (after subtracting the Dark Current) by dividing the FPA image by the FF calibration file. Note that the Flat-Field step for the SWIR band only corrects FPA artifacts---a separate calibration process is required for radiometric calibration.

FFcal = (FF – DC) / UF

FP2 = FP1 / FFcal *Flat-Field Formula*

Where:

FFcal = Focal Plane Flat-Field Calibration File.

UF = Pixel value of the Laboratory-prepared Uniform Field.

FF = Focal Plane Image of the Laboratory-prepare Uniform Flat Field.

DC = Focal Plane image of Dark Current.

FP2 = Flat-Field (and Dark Current) corrected Focal Plane image.

FP1 = Focal Plane image with Dark Current removed (from DC Formula).

In the unlikely event of a degrading Blackbody necessitating a TIR Flat-Field, a stable thermal mass would be imaged as a replacement for the Uniform Field (UF), in conjunction with a ground campaign simultaneously measuring the temperature of that mass. Candidate ground sites include water bodies and JPL's vicarious calibration sites [4].

3.3 Radiometric Calibration

For the five TIR bands, Level-1 Radiometric Calibration is the process of converting incident thermal energy (in Digital Numbers; DN) on the Focal Plane to calibrated radiance values. For testing and evaluation purposes, the radiance values are also converted to temperature values (degrees Kelvin). This is accomplished through: 1) Pre-Flight and In-Flight on-board measurement of the Cold (CBB) and Hot Blackbodies (HBB) temperatures; 2) Conversion of the known blackbody temperatures to Radiance using the Planck function; 3) Creation of Hot and Cold focal plane Blackbody Calibration and Radiance files; 4) Conversion of each focal plane DN to Radiance values using a two-point affine transformation; and 5) Use of the Inverse Planck function to convert each band's calculated pixel Radiance to Brightness Temperature (K). Laboratory testing indicates this radiometric calibration process is capable of better than 0.5 degree Kelvin error, which is half of the 1 degree Kelvin requirement [3].

3.3.1 Blackbody Temperature Measurement

Pre-flight Blackbody calibration is performed in the Laboratory on the flight hardware. This is particularly rigorous for ECOSTRESS because the FPA flight hardware is from the PHyTIR instrument that has been tested and evaluated numerous times [1]. The pre-flight process involves measuring the absolute skin temperature of each Blackbody (BB) using a NIST-traceable radiometer (National Institute of Standards and Technology) to derive Radiance versus Temperature correction factors. A second thermal camera is used to map spatial gradients in the surface of each BB, although no gradients (+/- 0.001 degree) have yet to be measured. The final adjustments (if any) will be measured before flight and provided as part of the general metadata.

In-flight measurement and monitoring of the Blackbodies is performed through the use of "platinum Resistance Temperature Detectors" (pt-RTDs) mounted on the backside of each Blackbody. Five pt-RTDs are spatially distributed across each Blackbody to accurately capture the temperatures, which are then downloaded as part of the Spacecraft's State-Of-Health metadata. The ground calibration process updates the measured Blackbody temperatures approximately once every minute.

The spacecraft's Hot Blackbody (HBB) is electrically heated with an expected constant nominal temperature of about 319 degrees Kelvin throughout the mission. The spacecraft's Cold Blackbody (CBB) is not explicitly managed and is allowed to drift with changes in the circulating fluids as affected by ISS activities and external space weather. The nominal range of drift is expected to be +/-0.5K over a period of days. The nominal pre-launch CBB is 293 degrees Kelvin, but could vary by +/-5K once fully configured with the ISS.

The In-flight calibration process should easily correct for drift and provide for an overall thermal calibration stability and accuracy of better than 0.050K [3].

3.3.2 Blackbody Conversion to Radiance

The two calibrated Blackbody temperatures are converted to spectral radiance using the center wavelength of each TIR band in the Planck function. Figure 2 provides the spectral response functions (SRF) for the five thermal bands.

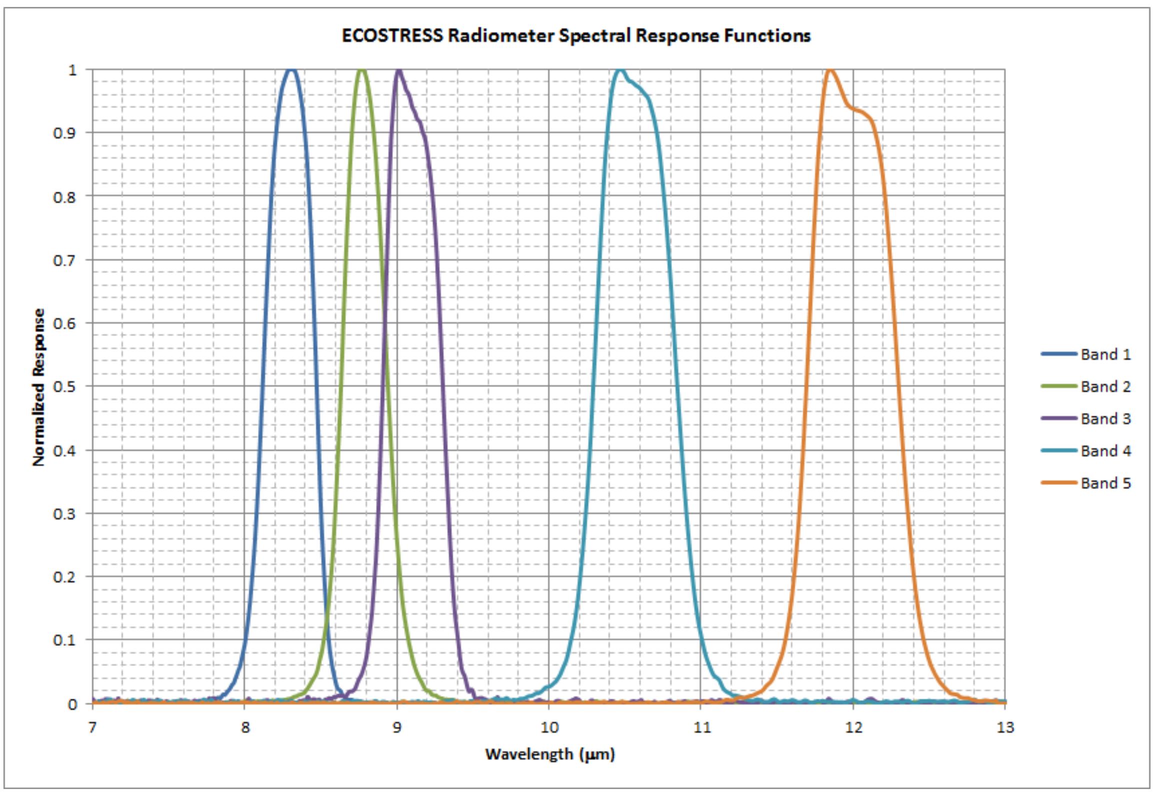

Figure 2: Spectral Response of the five ECOSTRESS Thermal Bands.

The Planck function converts blackbody temperatures (K) to spectral radiance. The standard algorithm is:

Planck (P) Function

$$L(\lambda,t) = \frac{c_1}{\lambda^5(e^{c_2/\lambda t}-1)}$$

Where:

$L(\lambda,t)$ = blackbody radiance (W/m^2-sr-um)

c_1 = 1.191042×10^8 (W/m^2-sr-um^{-4})

c_2=1.4387752×10^4 (K um)

λ = wavelength (um)

t = blackbody temperature (K)

(Source: WIKI/NOAA)

The Radiance of both the hot (R_h) and cold (R_c) blackbodies are calculated from the In-flight temperature metadata collected with each image set, which occurs approximately every minute.

Blackbody Radiance Formula

$$R_c = P(\lambda, Tc)$$

$$R_h = P(\lambda, Th)$$

Where:

R_c = *Radiance of the Cold Blackbody*

R_h = *Radiance of the Hot Blackbody*

P = *Planck Function (wavelength specific)*

T_c = *In-Flight collected Cold Blackbody Temperature (K)*

T_h = *In-Flight collected Hot Blackbody Temperature (K)*

3.3.3 Blackbody DN Calibration Files

With each half-rotation of the mirror scan (about every 1.18 seconds), the focal plane (with 6 filters) collects the Digital Numbers (DNs) across the Cold and Hot Blackbodies and the ground image. Sixty-four (64) focal planes are collected over each Blackbody (64x256) and 5400 focal planes are collected over each Earth image (Figure 3).

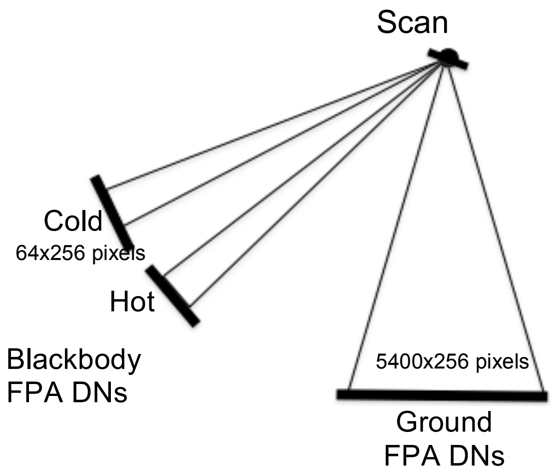

Figure 3: A Single Scan of the Mirror Images two Blackbodies and the Earth in each Wavelength.

The 64x256 pixel DN scans of the two blackbodies are appended to the L0 image data for download and later extraction. On the ground, 44 scans are combined to form full Blackbodies and images (44x256=11264 pixels). The 64 pixels in each Blackbody DN file are averaged from 64 (by 11264) to 1 pixel (by 11264) to produce very precise DN focal plane measurements that can be aligned with the single pixel-width radiance images generated in Section 3.3.2.

3.3.4 DN to Radiance Two-Point Conversion

Given the FPA Radiance values (Section 3.3.2) and the corresponding FPA DNs (Section 3.3.3) for both the Cold and Hot Blackbodies, it is possible to perform a two-point affine transformation that converts each unique input pixel DN from the focal plane directly to Radiance. Dark Current and basic FPA artifacts are implicitly corrected in the process. The linearity fit between the two blackbodies for each pixel are output as Gain and Offset terms.

Two-Point Calibration Formula

$$R_\lambda = a + bD_\lambda$$

$$a = \frac{R_h D_c - R_c D_h}{D_c - D_h} \qquad b = \frac{R_c - R_h}{D_c - D_h}$$

Where:

R = Calculated Radiance of an input Digital Number (DN)

a = Offset Term

b = Gain Term

D = Input Earth Digital Number (DN)

R_c *= Radiance of the Cold Blackbody (Section 3.3.2)*

R_h *= Radiance of the Hot Blackbody (Section 3.3.2)*

D_c *= Digital Number (DN) from the Cold Blackbody Calibration File (Section 3.3.3)*

D_h *= Digital Number (DN) from the Hot Blackbody Calibration File (Section 3.3.3)*

Each full Blackbody and ground collection set of 44 scans by 5400 focal planes (by 6 bands) is imaged every 52 seconds. Gain and Offset terms are uniquely calculated for each of the 44 scans and applied uniformly within each scan. The product of the L1A CAL calibration (Figure 1) are the Gain and Offset files. In production processing, the ECOSTRESS image will be resampled and geolocated before the Gain and Offset files are applied to create Radiance images.

3.3.5 Radiance to Temperature Conversion

However, for validation purposes a number of test images will be converted from DN to radiance and brightness temperature (Kelvin) to verify their accuracy is within 1 degree (at 300K). The conversion from radiance to temperature is performed using the inverse Planck Function:

Inverse Planck Function

$$t(\lambda, L) = \frac{c_2}{\lambda \ln(c_1 / \lambda^5 L + 1)}$$

Where:

t = blackbody temperature (K)

L = blackbody radiance (W/m^2-sr-um)

c_1 = 1.191042×10^8 (W/m^2-sr-um^{-4})

c_2 =1.4387752×10^4 (K um)

λ = wavelength (um)

(Source: WIKI/NOAA)

4 External Dependencies and Potential Issues

There are no external data dependencies for Level-1 Radiometric Calibration of the five ECOSTRESS thermal bands.

There are no external data dependencies for Level-1 Focal Plane Calibration of the SWIR band.

Level-1 Radiometric Calibration of the SWIR Reflectance band is not required for its expected use in supporting Geolocation. If it becomes necessary, a calibration campaign may be performed involving over-flights of a pre-determined location where vicarious field measurements of spectral reflectance, sun position, and weather can be combined with coincident atmospheric parameters [4].

5 Validation

Radiometric thermal calibration has been extensively tested and validated in the Laboratory as part of the earlier PHyTIR instrument program [1]. This included skin temperature measurements of large stable lakes (i.e., Lake Tahoe; Salton Sea) compared with sensor radiance measurements. These tests will be repeated as appropriate (Section 3.3.5) to validate the sensor for the ECOSTRESS mission, and after installation on the International Space Station, performed through integrated instrument and ground data processing activities.

6 References

[1] Johnson, W.R., S.J. Hook, M. Foote, B.T. Eng, and B. Jau, 2014. "Characterization and Performance of the Prototype HyspIRI-TIR (PHyTIR) Sensor," Proceedings of SPIE, Vol. 9222, 922208, 12 pages.

[2] Hulley, G.C., and S.J. Hook, 2015. "ECOSTRESS Level-2 Land Surface Temperature and Emissivity Algorithm Theoretical Basis Document (ATBD)," NASA/Jet Propulsion Laboratory internal ECOSTRESS Project Document, California Institute of Technology, 103 pages.

[3] Goullioud, R., 2015. "ECOSTRESS_Error_Budget_2015-04-08.xlsm," NASA/Jet Propulsion Laboratory internal ECOSTRESS Project Document, California Institute of Technology.

[4] Helmlinger, M.C., C.J. Bruegge, E.H. Lubka, and H.N. Gross, 2007. "LED Spectrometer (LSpec) Autonomous Vicarious Calibration Facility." Proceedings of SPIE, Vol. 6677, 10 pages.

[5] Barbieri, R., etal., 1997. "Draft of the MODIS Level 1B Algorithm Theoretical Basis Document Version 2.0 [ATBMOS-01]. SAIC/GSC MCST Document. 68 pages.